Advanced Satellite-Derived Wind Observations, Assimilation, and Targeting Strategies during TCS-08 for Developing Improved Operational Analysis and Prediction of Western Pacific Tropical Cyclones

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LONG-TERM GOALS

Forecasts of tropical cyclone (TC) formation and intensity change in the north-western Pacific basin are often lacking in skill, in part due to the paucity of conventional oceanic observations that are assimilated into the operational models. This lack of observations has also constrained our understanding of how TC formation is governed by environmental processes. Recently, remotely-sensed observations from satellites have become a routine and important input to the global data assimilation systems. These data can provide critical environmental data for the testing of hypotheses of TC formation and development, and improving our understanding of how environmental influences on TC structure evolve up to landfall or extratropical transition. In particular, winds derived from geostationary satellites have been shown to be an important component of the observing system in reducing TC model track forecasts. However, in regards to TC formation, intensity change, and extratropical transition, it is clear that a dedicated research effort is needed to optimize the satellite data processing strategies, assimilation, and applications to better understand the behavior of the near-storm environmental flow fields during these evolutionary TC stages. To our knowledge, this project represents the first time anyone has tried to evaluate the impact of targeted *satellite* data on TC forecasts using an automated dynamic targeted observing strategy. TCS-08 afforded us the opportunity to employ specially-processed satellite data along with observations collected in situ by the NAVY P-3, and other platforms, to investigate these objectives as they apply in the western north Pacific TC basin. The development of successful real-time strategies to optimally assimilate wind data from satellites will ultimately lead to the provision of improved initial and boundary conditions for the Navy's envisioned mesoscale coupled ocean-wave-atmosphere forecast model.

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OBJECTIVES

The ultimate objective of this project is the development and refinement of a capability to supplement the contemporary atmospheric observation network with advanced satellite wind observations to improve high-resolution operational analyses and medium-range forecasts of western North Pacific typhoons.

One primary research goal is to evaluate and diagnose the impact of assimilating the advanced satellite wind observations on global Navy model forecasts, and high-resolution forecasts of structure change. We aim to better understand how to utilize the satellite wind data in the context of numerical model assimilation and forecast impact. Optimizing the assimilation of the experimental satellite winds will involve a continued investigation of the satellite data impacts with respect to objective targeting of analysis-sensitive regions, and utilizing 4DVAR approaches.

APPROACH

During the field phase of TCS-08, experimental satellite-derived wind observations were produced by UW-CIMSS using state-of-the-art automated methods. Hourly datasets were routinely derived from operational images provided from the Japan Meteorological Agency (JMA) MTSAT geostationary satellite. In addition, special rapid-scan (r/s) images from MTSAT-2 were provided by JMA for extended periods (24-48hrs) over specific regions, and including parts of selected typhoon life cycles. UW-CIMSS also processed these images into wind fields (higher resolution). These special satellite-derived wind observations complemented those data collected by the NRL P-3 aircraft during TCS-08, by providing unique time-continuous environmental data in locations that were deemed important to tropical cyclone formation and development.

The project uses the latest versions of the NRL Atmospheric Variational Data Assimilation System – Accelerated Representer (NAVDAS-AR) and NOGAPS, the Navy's current operational data assimilation and global forecast model systems, so that the research results may be easily transitioned to improve the Navy's operational predictions. We expect that the NAVDAS 4DVAR assimilation will provide an improved analysis, since its temporal continuity better exploits the asynoptic satellite winds than 3DVAR, in which the observations are assimilated at discrete 6-hour intervals. Upon completion of the experiments, the resulting global analyses and forecasts will be made available to investigators involved in developing and testing the Navy's coupled ocean-wave-atmosphere model.

Existing adaptive observing strategies such as the Ensemble Transform Kalman Filter (ETKF) and NOGAPS Singular Vectors have been used to identify regions in which numerical forecasts are most likely to benefit from the assimilation of additional satellite wind data. A new 'synthetic observation ensemble' will also be devised to answer this question more directly. Via the observation sensitivity method (for forecasts up to 24h) and data denial in the Navy forecast system (for forecasts up to 5 days), the impact of assimilating targeted high-density (hourly and rapid-scan) satellite winds on global model forecasts of tropical cyclone track and high-resolution forecasts of tropical cyclone structure will be evaluated and analyzed.

Finally, in order to extend and evaluate targeting hypotheses specific to high-resolution predictions of tropical cyclone structure, new perturbation experiments in the Weather Research and Forecasting

(WRF) modeling framework are being designed. This framework allows for the direct diagnosis of how modifications to the initial wind field in the synoptic environment lead to altered forecasts of tropical cyclone structure. The software is designed such that it can be transferred to the developing COAMPS-TC framework at the Naval Research Laboratory, Monterey.

WORK COMPLETED

In Year 3, the UW-CIMSS team collaborated with scientists at NRL-MRY to conduct data impact studies using the specially processed AMV datasets produced from MTSAT by CIMSS, as described in previous reports. A series of experiments to quantify the impact of the MTSAT AMVs during TCS-08 have been performed at NRL Monterey using the operational version of the NAVDAS-AR, which is a full 4-dimensional variational (4d-Var) algorithm solved in observation space with a weak constraint formulation that allows the inclusion of model error. It uses asynoptic and single-level data more effectively than the earlier 3d-Var NAVDAS system. AMVs in NAVDAS-AR are assimilated using a "super-ob" pre-processing approach that combines raw wind observations into averages within 1° latitude-longitude prisms in 50 hPa layers. It is the super-ob winds that are then actually assimilated.

The primary task of the U. Miami team in Year 3 was to complete the detailed investigation of the synoptic sensitivity associated with one long-lived cyclone during TCS-08: Typhoon Sinlaku, and the evaluation of hypotheses for optimal areas for targeting satellite wind data. A graduate student funded on this grant, William Komaromi, was trained on the usage of the WRF model framework necessary to conduct the numerical experiments for his thesis research. In order to better diagnose the locations in which forecasts are most likely to benefit from the assimilation of targeted satellite AMVs, a new perturbation technique was developed. This technique is an *analysis sensitivity* method, which bypasses observations, data assimilation and their associated inaccuracies. Unlike existing the techniques used for adaptive observations in tropical cyclones, such as Singular Vectors and the ensemble transform Kalman filter, this technique is not based on an assumption that the dynamics are linear. Instead, the vorticity field is perturbed in a local region at the initial time, and the flow is re-balanced to produce a new perturbed analysis. The WRF model is then integrated forward to provide a perturbed forecast, which is compared with a 'control' forecast in which no perturbation is made to the initial conditions.

RESULTS

From the UW-NRL investigations, the hourly MTSAT AMV datasets were first assimilated in NAVDAS-AR for the two- month TCS-08 period. The hourly AMVs allow for more consistent temporal coverage of the evolving atmospheric flow. This baseline analysis also includes all conventional and special T-PARC observations except for dropwindsondes and rapid-scan AMVs, and is referred to as the control (CTL). Two additional experiments were produced: (i) "No-AMV" which is CTL with the CIMSS hourly winds removed, and (ii) "Rapid-Scan" which is CTL but with the rapid-scan AMVs included. For NOGAPS forecasts of length exceeding 3 days, the average error of the tropical cyclone track forecasts is reduced considerably due to the assimilation of the hourly AMVs (Table 1). The same forecasts were also improved further by the inclusion of rapid-scan winds. For example, for 4-day forecasts, the average track error was reduced by ~30% when hourly winds were included, and by ~45% when both hourly and rapid-scan winds were included. Furthermore, the number of forecasts of very large error, which may be considered "busts", was reduced by the assimilation of AMVs (Fig. 2a), and the average forecast error was reduced further when a lower weight was given to the bogus vortex used in the operational NOGAPS system (Fig. 2b). Another potential reason for the improved forecasts through assimilation of hourly and rapid-scan wind data is the superior representation of transient mid-latitude troughs that act to modify the track and structure of the typhoon. For example, the assimilation of the rapid-scan AMVs produces a slower NOGAPS forecast track that is closer to the verification than that produced when rapid-scan winds are neglected (Figs. 2c, d). It should be noted that there were considerable errors and uncertainty in the operational forecasts of Typhoon Sinlaku, which has been the primary TCS-08 case under investigation and during which rapid-scan mode was activated for three days.

TABLE 1. NOGAPS track forecast errors (in nm) for the three NAVDAS/NOGAPS numerical experiments, over all tropical cyclone cases during TCS-08.

Fcst (hrs)	0	12	24	36	48	60	72	84	96	108	120
CTL w/ AMV	22	39	70	93	114	151	213	195	167	248	317
No-AMV	22	40	67	91	108	154	227	248	245	365	450
Rapid-Scan	25	45	78	111	122	158	210	174	135	215	250
# cases	22	20	18	16	14	13	12	11	9	8	7

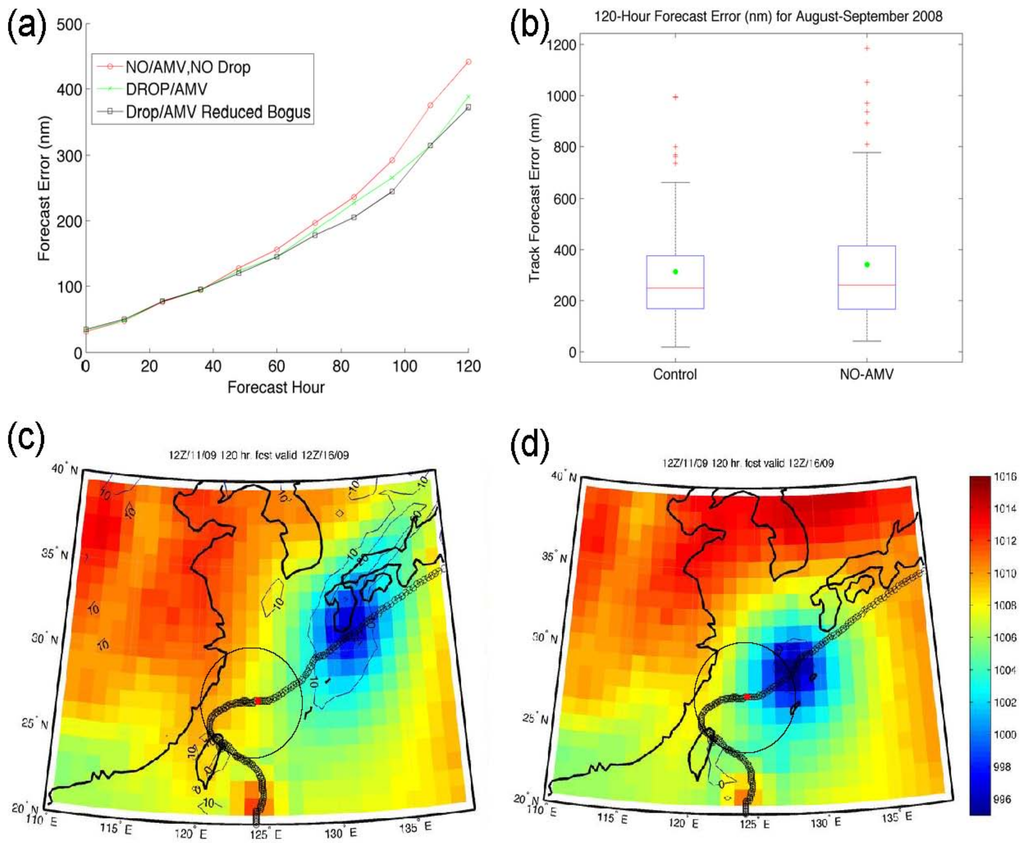

FIGURE 2. Top: (a) NOGAPS track forecast errors for tropical cyclones during August-September 2008. (b) Errors of 120-hour forecast tracks, illustrating the reduced number of cases of very high forecast error when AMVs are included (Control). Bottom: 120-hour forecasts of sea level pressure of Typhoon Sinlaku and its environment for (c) hourly winds assimilated and (d) hourly and rapid-scan winds assimilated in NAVDAS-AR. Typhoon Sinlaku is represented by the area of lowest pressure (blue shading). The verifying position of Sinlaku is marked as a red dot along the best track (black line).

The University of Miami perturbation technique has been applied to the case of Typhoon Sinlaku, with the strongest sensitivity in the track forecast found due to perturbations in the upper-level shortwave trough 1000 km to its north (denoted 'S2' in Fig. 3a), and a trough upstream in the mid-latitude storm track (denoted 'S1' in Fig. 3a). The weakening of the upper-level trough in the perturbed run 'S2' acted to decrease the northward component of the flow in the environment of Sinlaku, keeping the typhoon further south, consistent with the actual track (Figs 3b, c). The mid-latitude sensitivity is a potential reason for the improvement of the >3-day NOGAPS forecasts in Figs 2c and 2d, in which hourly and rapid-scan AMV data were assimilated for several days over broad target areas in the near and far vicinity of Typhoon Sinlaku.

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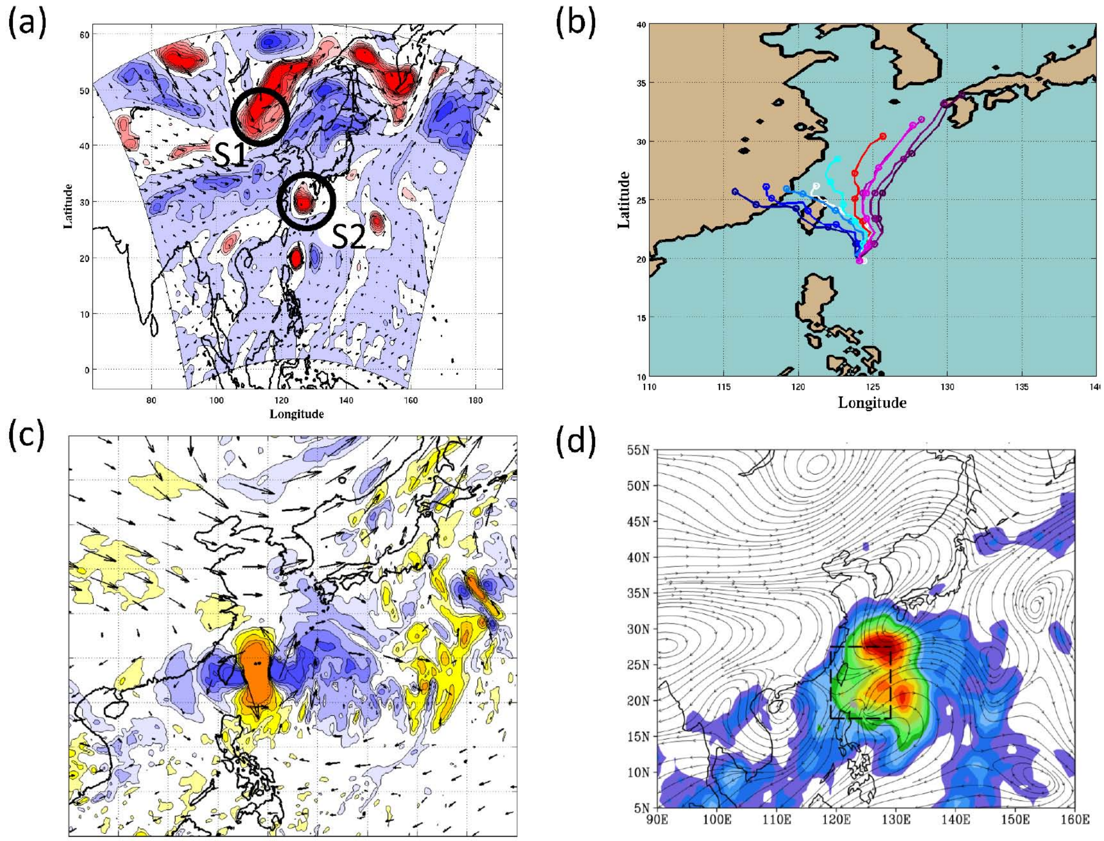

FIGURE 3. (a) 500-200 hPa layer averaged relative vorticity (red=positive, blue=negative), for the case of Typhoon Sinlaku at 0000 UTC 10 September 2008. The labels S1 and S2 refer to two locations in which the vorticity is perturbed in the 500-200 hPa layer. (b) WRF track forecasts of Typhoon Sinlaku initialized at the same time, for the control (white track) and the S2 perturbation for a range of strengths of perturbation. (c) Difference in 850-200 hPa mean meridional wind between the perturbed WRF simulation closest to the best track (blue in Fig. 3b) and the control WRF simulation, at 96 h. (d) ETKF guidance for observing 200 hPa horizontal wind to improve a 2-day forecast of Sinlaku initialized on 10 September 2008, based on the ECMWF, NCEP and CMC ensembles.

While the vorticity perturbation technique is expected to offer cleaner insights on analysis sensitivity than is possible with data assimilation, it is not suited for real-time use as a predictive sensitivity method, given its computational expense. Its primary use will be for retrospective diagnoses to understand the sensitivities in subsequent targeting experiments. The final part of our proposed research will use the synthetic observation ensemble, described in the initial proposal, to select broad areas for targeting of supplementary hourly and rapid-scan winds. Targets using this method will be compared with the Singular Vectors available at NRL, and the University of Miami modified ETKF approach (Fig. 3d).

IMPACT/APPLICATIONS

A quantitative understanding of the influence of improved representations of the synoptic environment and outflow in the tropical cyclone will lead to new scientific conclusions on environmental interactions and modifications to tropical cyclone track and structure. The longer-term impact will be derived from the improved assimilation of targeted satellite wind observations in Navy (and other) models.

RELATED PROJECTS

This project is related to that funded by the TCS-08 grant N000140810250: “Using NOGAPS Singular Vectors to Diagnose Large-Scales on Tropical Cyclogenesis” (PI Majumdar; Co-PIs Peng and Reynolds of NRL Monterey). A supplement to the budget on that grant has enabled the further development of the WRF vortex initialization and inversion software for easy use by students and collaborators. This software will also be used in the new NOPP collaboration between Velden and Majumdar cited below.

This project is also related to that funded by NOPP grant N00014-10-1-0123: “Achieving Superior Tropical Cyclone Intensity Forecasts by Improving the Assimilation of High-Resolution Satellite Data into Mesoscale Prediction Models” (PIs Velden and Majumdar, Co-PIs Doyle and Hawkins of NRL-MRY).

PUBLICATIONS

Berger, H., C.S. Velden, R. Langland and C. Reynolds, 2010: Atmospheric motion vector impact on NOGAPS typhoon forecasts during TPARC/TCS-08. Wea. Fore. [submitted, refereed]

Majumdar, S. J., S.-G. Chen, and C.-C. Wu, 2010: Characteristics of Ensemble Transform Kalman Filter adaptive sampling guidance for tropical cyclones. Quart. J. Roy. Meteor. Soc. [accepted with minor revisions, refereed]

Komaromi, W. A., S. J. Majumdar and E. D. Rappin, 2010: Diagnosing initial condition sensitivity of Typhoon Sinlaku (2008) and Hurricane Ike (2008). Mon. Wea. Rev. [submitted, refereed]

HONORS/AWARDS/PRIZES

PI Velden elected as Co-Director of the Seventh WMO International Workshop on Tropical Cyclones to be held in November, 2010. PI Velden also nominated to serve as Councilor for the American Meteorological Society.